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# A Systematic Review of Sensing and Control Strategies of Wearable Active Ankle Exoskeletons/Exosuits, With Performance Assessment Based on a Complexity Index

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**ABSTRACT** Many people worldwide suffer from motor impairments, with aging and stroke being two of the main causes, resulting in limited mobility for carrying out activities of daily living, reduced walking speed, increased metabolic consumption, and higher risk of falling. Exoskeletons are widely seen as a promising assistive technology for addressing these major challenges and mitigating the impacts of motor impairments. This review provides a comprehensive assessment of wearable active exoskeleton technologies, including their sensing, actuating, and control strategies, for elderly support in healthy aging applications. Specifically, we focus on actuators, sensors, and control strategies for active exoskeleton technologies applied to the ankle joint, as these play a critical role in human mobility assistance. By defining a complexity index that accounts for both mechanical and computational complexity of different exoskeleton solutions, we provide a comparative analysis of the landscape and conclude with a new perspective on future trends in soft, wearable, and modular ankle exoskeleton technologies.

**INDEX TERMS** Assisted mobility, exoskeletons, exoskeleton complexity index, motion intention prediction, wearable sensors.

## I. INTRODUCTION

One billion people were over the age of 60 in 2019, and 110 million people were stroke survivors in 2024, and these numbers are on the rise [1], [2], [3]. Aging comes with a weakening body, reduction of muscle force, and increased fall prevalence [4], [5], [6], [7], [8], [9]. Biomechanical alterations are observed in the gait of older adults, notably from the age of 60, as a consequence of multiple changes occurring in the muscular and nervous systems, which are manifested as impeded walking patterns and increased associated metabolic consumption [10]. Stroke is associated with impaired motor coordination [11], muscle weakness and spasticity [12], and reduced ankle dorsiflexion, resulting in limited walking speed and gait compensations by hip hiking or circumduction of the paretic limb and increased risk of falling and metabolic consumption [2], [13], [14], [15], [16], [17].

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**FIGURE 1.** **Wearable active ankle exoskeletons can be classified based on their rigidity, actuation, sensing, and control strategies. In this review, devices are assessed based on their metabolic benefits and device weight, as well as our proposed complexity index.**

The ankle joint is essential for human locomotion, as it produces more mechanical power than either the knee or the hip and is key to maintaining balance during gait. It is affected by both aging and stroke, making it responsible for the limited mobility of the target individuals [2], [18], [19]. In the case of stroke, dorsiflexor weakness causes foot slap at heel strike, and foot drop and toe drag during the swing phase of the gait cycle, while plantarflexor weakness impedes stability and propulsion [2], [20]. Assisting the ankle joint has been shown to provide optimal metabolic consumption benefits [21], as increasing the mechanical power output of the ankle can decrease the power demands on the hip, leading to improved walking efficiency [19].

Exoskeletons are widely seen as a promising technology for providing physical assistance to the user's gait. In particular, we focus here on devices incorporating active mechanical elements and providing additional power [22], as otherwise passive devices, despite being lightweight, have limited controllability and struggle to break the metabolic consumption barrier, being unable to provide enough positive power to overcome the added device mass [23], [24], [25]. Wearable untethered exoskeletons can be integrated into the user's lifestyle and used during daily activities, which presents an advantage over platform and tethered exoskeletons that can only be used for training and rehabilitation in a clinical setting. While the earliest forms of exoskeletons have been around since 1890 [26], significant progress has been made in recent years and is still underway, with lighter and softer devices being developed.

Ankle exoskeletons have been reviewed in the literature, but an up-to-date comprehensive review is lacking. Many reviews include little to no soft devices [27], [28], [29], [30], [31], [32], or do not elaborate on the sensors and control methods used in each device [29], [30], [33]. The latest review [34] only includes soft devices/exosuits for ankle assistance (and commercial rigid exoskeletons for multijoint assistance). Another review [26] only includes publications between 2019 and 2022 and does not distinguish between soft and rigid exoskeletons. While exosuits were reported in three of the selected papers, only one of them targets the ankle joint. While [2] is the most comprehensive among these reviews in terms of classifying devices on the bases of rigid/soft, sensing, actuation, and control, further progress has been made since then, as more devices have been developed, or control strategies of existing designs were improved.

Exoskeletons frequently focus on reducing the effort associated with movement by optimizing metabolic consumption, either just by offsetting the added device mass and keeping the same metabolic consumption levels as during unassisted movement or providing further savings and improved performance [35], [36]. An important criterion to be optimized in exoskeleton design is device weight, as increasing exoskeleton weight impedes gait (increased step length, decreased step height [37]) and dynamic balance [38] and increases metabolic consumption, especially when the weight is added distally on the legs [39], [40]. Another factor to be considered is complexity, as less complex devices tend to be lighter, are easier to use, require less complex controllers [41], and, therefore, have a lower risk of malfunctions and are inherently safer, more cost efficient, and easier to prototype, iterate, test, and go through regulatory approval processes. None of the previously mentioned reviews considered these factors.

In this article, we present a systematic review capturing the latest advancements in wearable active ankle exoskeletons, both rigid and soft/exosuits, and exploring their sensing modalities, actuation, and control strategies (Fig. 1).

We introduce a complexity index to measure the design complexity of ankle exoskeletons and observe the interrelations between complexity, weight, and metabolic savings over the years.

## II. METHODS

2008 was selected as the start year for this review, after considering the most important active wearable devices that were developed before 2008, and which were included in the aforementioned ten reviews [42], [43], [44], [45], [46], [47], [48], [49]. Notably, all these devices are rigid exoskeletons. In most cases, the devices were found to be physically connected to an external air source, a controller, or a power source. The device in [48] is claimed to be portable and wearable in a compact 0.95-kg package, but no information on sensing and control was provided. The device in [46] was deemed portable by the authors, claiming that a micro air compressor by Kinetic Muscles Inc., which fits in a very small box, can be used to power the device and can, therefore, be considered as the only device that would have met the inclusion criteria of our review but was developed before the time frame considered.

A literature search was conducted on articles published between 2008 and 2024 in IEEE Xplore, PubMed, Science Direct, Web of Science, and Scopus, using the keywords "exoskeleton" OR "exosuit" OR "orthosis" OR "robot" (in the title) AND "ankle" (in any field). Inclusion criteria are: 1) new (or improved) device; 2) a physical prototype has been completed; 3) the device is wearable and untethered, i.e., does not have wired connections to any controllers, power supplies, air compressors, etc.; parallel/platform robots were excluded; 4) an active actuator is used; 5) the device is fully contained and self-controlled, i.e., the control algorithm runs onboard, without the need to connect to a computer even wirelessly; 6) single-joint (ankle) devices; and 7) used for walking (in-bed and underwater devices were excluded). After filtering out duplicates, review articles and papers describing multijoint exoskeletons or those that assist any joints other than the ankle, parallel/platform robots, and nonassistive robots (e.g., bipeds and humanoids) were discarded. Among the remaining titles, potentially relevant papers were highlighted and thoroughly examined for wearability; data on the actuators, sensors, and control methods used; whether the device is rigid or soft; the target users for the proposed devices; and the year of publication. The collected data were further analyzed to extract information on the device weights, metabolic benefits, type of assistance (unilateral or bilateral), degrees of freedom (DOFs), and numbers of sensors and actuators.

## III. RESULTS

A total of 12 511 search results were obtained (870, 904, 1270, 2189, and 7278, in order), including 4187 duplicates. A total of 254 potentially relevant papers were highlighted for full-text examination (140, 31, 20, 41, and 22, respectively). Eventually, a total of 79 papers (36, 12, 5, 21, and 5, respectively) were selected [20], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127]. Fig. 3 shows pictures of some of the latest state-of-the-art exoskeletons.

In total, 54 articles out of 79 included mentioned the weight of their proposed devices. A total of 13 exoskeletons overall were reported to provide metabolic benefits, but the device weight is unknown for two of them ([112] rigid bilateral, –20% $VO_2$ versus unpowered/uncoupled, 2014; [77] hybrid bilateral –17.4% (incline) and –27.8% (stairs) in cost of transport (W/kg) versus no device, 2021); hence, only the remaining 11 devices are included in the subsequent paragraphs.

## IV. RIGID VERSUS SOFT ANKLE EXOSKELETONS

Exoskeletons have long consisted of rigid structures and actuators made of solid materials. Recently, soft exoskeletons or exosuits have been introduced. These either have soft actuation or force transmission, which is made of flexible and soft materials, such as textile, Velcro, and straps. Many devices, however, can be a hybrid combination of both and, therefore, cannot be considered as fully soft exoskeletons [34].

Rigid exoskeletons still make up the majority, with 50 (63.3%) devices overall belonging to this category (see Fig. 2) [20], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [64], [67], [68], [69], [75], [79], [80], [84], [88], [89], [90], [92], [93], [94], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [115], [116], [118], [122], [124], [126]. While 20 (25.3%) devices were fully soft [62], [65], [66], [70], [72], [76], [78], [82], [83], [85], [86], [87], [114], [117], [119], [120], [121], [123], [125], [127], nine devices fell into the hybrid category as they had a significant rigid part (e.g., brace, electronics, etc.) [63], [71], [73], [74], [77], [81], [91], [95], [113].

## V. ACTUATION

Ankle exoskeletons are commonly actuated using pneumatic actuators, direct motor drive, and compliant actuators, in particular, series elastic actuators (SEAs). Nonetheless, other actuators have been found in the literature: the actuator in [50] is actuated by two solenoids, and Allen et al. [95] adopted a dielectric elastomer actuator, which is in essence an electroactive polymer that converts electrical energy to mechanical work and is a type of expandable artificial muscle; the actuators in [53] or [109] have electrohydraulic actuation, combining a dc motor, a hydraulic pump, and nylon-coated steel cables.

### A. PNEUMATIC ACTUATORS

A total of 12 devices had pneumatic actuators (see Fig. 2) [20], [56], [62], [69], [89], [90], [99], [114], [117], [118], [124], [126]. Their main benefits are a high torque-to-weight ratio

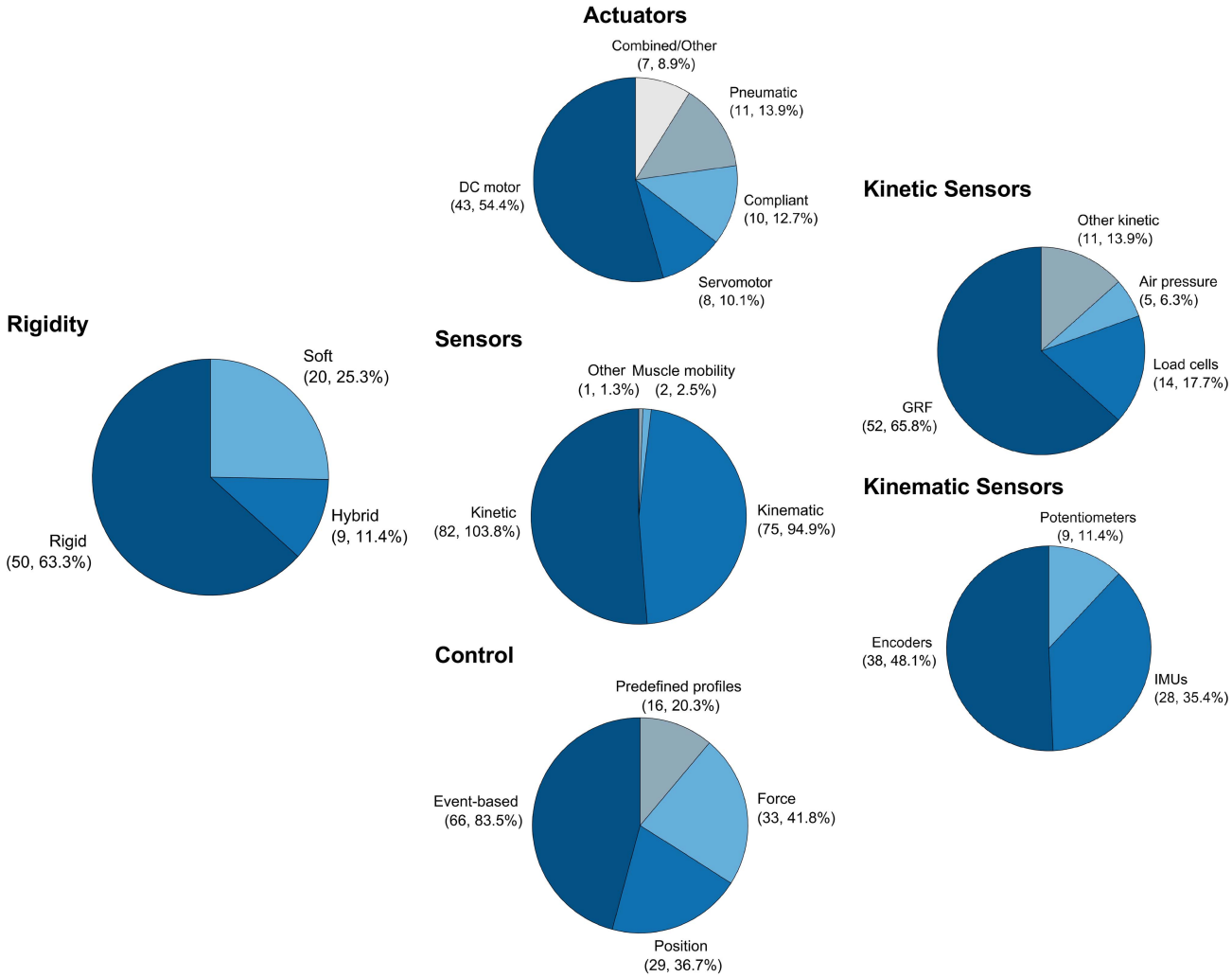



**FIGURE 2.** Distribution of the 79 reviewed exoskeletons by rigidity, actuators, sensors, and control strategies.

and natural compliance [2]. While another advantage is their light weight when combined with remote power transmission, such devices are no longer fully contained [128].

### B. COMPLIANT ACTUATORS

Several compliant actuators were recently proposed and applied in exoskeletons for their inherent safety and comfort in human–robot interaction. They can be either SEAs, consisting of a dc motor in series with a spring via mechanical transmission, or variable stiffness actuators (VSA) in which stiffness can be adjusted and regulated [129]. In an SEA, the output force can be controlled by adjusting the compression of the spring and is commonly used in lower limb exoskeletons, as well as in prostheses and walking robots [130], [131]. Its advantages include its low impedance; high control precision; energy storage; filtering of backlash, torque ripple, and friction by the spring; and isolation of the shock load from the motor [132]. However, it is bulky, heavy, and has a complicated structure [2], [133]. Ten exoskeletons are actuated by an SEA [58], [75], [93], [96], [103], [105], [108], [115], [119], [122]. Ward et al. [93] used a robotic tendon actuator, consisting of a dc motor coupled to a leadscrew and lead nut with a series spring. VSAs normally need additional motors to adjust stiffness. For instance, Moltedo et al. [75] designed their own mechanically adjustable compliance and controllable equilibrium position actuator, which includes dc motors and a Dyneema rope.

### C. DIRECT-DRIVE ACTUATORS

The most common actuators in ankle exoskeletons are motors that are directly coupled to outputs [51], [55], [57], [59], [61], [64], [79], [81], [91], [92], [94], [97], [98], [102], [106], [111] and are frequently combined with ropes and Bowden cables [60], [63], [65], [67], [68], [70], [71], [72], [73], [74], [76], [77], [78], [82], [83], [84], [85], [86], [88], [112], [113], [116], [121], [123], [127], which is particularly beneficial as soft actuation in exosuits. Some devices report having linear actuators, which are in essence electric motors with a mechanical transmission that transforms the rotation of the motor into linear motion: Awad et al. [125] used a linear actuator

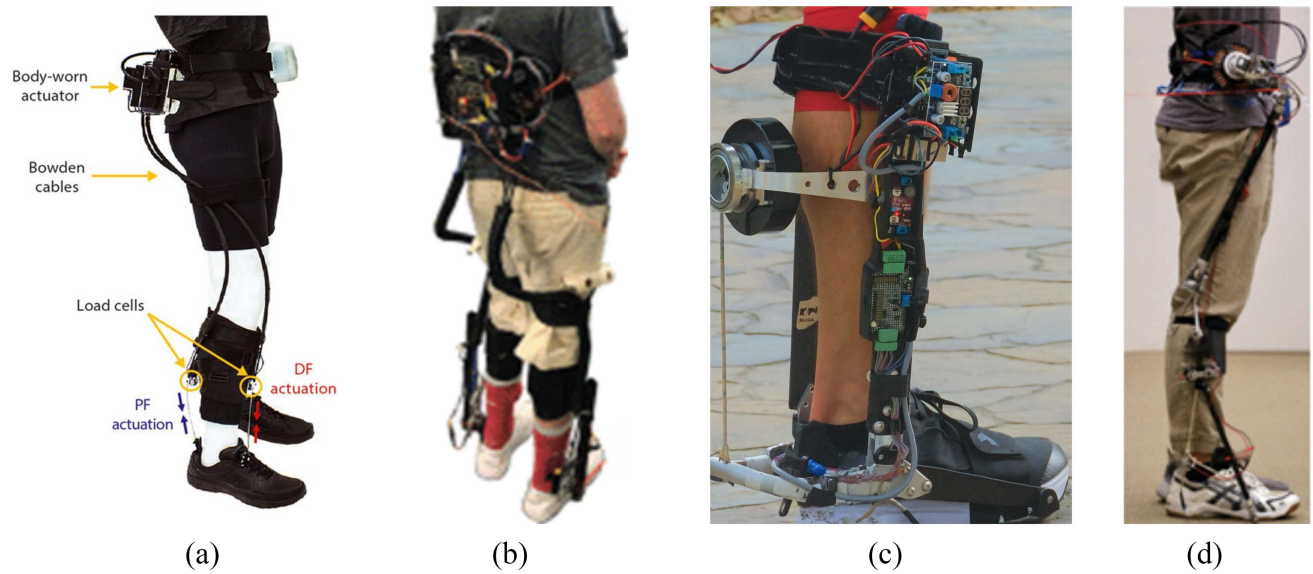



**FIGURE 3.** Some of the latest state-of-the-art ankle exoskeletons: (a) 2017 [125], (b) 2020 [63], (c) 2022 [88], and (d) 2023 [67].

with Bowden cables, while Chin et al. [89] combined a linear actuator with an onboard pneumatic pump. Other direct-drive actuators (DDAs) are reported as well. Mooney et al. [80] used a winch actuator powered by a brushless dc motor. Yin et al. [100] used a virtual muscle mechanical model, simplified as a muscle–tendon complex, which included a dc motor with a Bowden rope; Orekhov and Lerner [66] used a parallel elastic actuator, consisting of a leaf spring assembly and a Bowden-cable-actuated pulley. Servo motors can also be employed [52], [54], [101], [104], [107], [110] and paired with Bowden cables as well [87], [120].

## VI. SENSING

Exoskeletons rely on sensors to provide necessary information for their control system in order to detect gait phases and measure the joint angle, the assistance provided (force/torque, spring deflection, and motor rotation), or electromyography (EMG) muscle signals. Hence, Shi et al. [2] classified the sensors used in ankle exoskeletons in three categories based on the type of information they provide: 1) kinetic; 2) kinematic; and 3) muscle mobility. The vast majority of the reviewed articles used commercially available sensors, such as piezoresistive Tekscan FlexiForce A-series [61], [63], [77], [79] or polymer thick film Interlink Electronics FSR-402 [50], [52], [82] force sensing resistors (FSRs), XSens 9-axis MTi inertial measurement units (IMUs) [60], [70], [74], and Futek 17-4 PH S.S. load cells with shielded Teflon cables [67], [70], [74]. Few articles proposed novel sensor systems, such as [65] where the authors designed their custom FSR insole; [69] whose authors used their own optical-type 2-D ground reaction force (GRF) sensors based on a deformable flexure structure, reflective surfaces, and reflective optical sensors [134]; [84] whose authors made their custom, thin, and lightweight torque transducer with machined 7075-T651 aluminum instrumented with strain gages to bidirectionally measure up to 30 N·m of torque; and [86] where authors introduced a shear wave tensiometer [see Section VI-C2].

### A. KINETIC SENSORS

#### 1) GROUND REACTION FORCE SENSORS

FSRs or pressure sensors, foot switches, and sensor-embedded insoles all come under this category [20], [50], [51], [52], [54], [55], [56], [58], [61], [62], [63], [64], [65], [66], [67], [68], [69], [71], [73], [77], [79], [82], [83], [84], [87], [88], [89], [90], [92], [93], [94], [95], [96], [97], [98], [99], [101], [102], [103], [105], [106], [108], [110], [111], [113], [114], [115], [117], [120], [123], [124], [126]. They are used to detect contact of specific regions of the foot (e.g., heel strike, toe off) and transitions between gait phases, usually along with finite-state machines (FSMs), to perform event-based control.

#### 2) AIR PRESSURE SENSORS

These are used along with pneumatic actuators [55], [62], [69], [89], [117].

#### 3) OTHER TYPES OF FORCE SENSORS

Several devices have load cells [60], [68], [70], [73], [74], [82], [83], [85], [86], [94], [120], [121], [125], [127], strain gauges [67], [84], [88], tension [100], and force and displacement [78] sensors, which are commonly used along with ropes and Bowden cables, to measure the applied force transmitted by the cables. Other sensors in this category include torque [63], [71], [77], [79] and current sensors [105], [108]. These sensors allow for force-based control [125].

### B. KINEMATIC SENSORS

#### 1) ENCODERS AND POTENTIOMETERS

These sensors are used to measure actuator output (motor rotation and spring/cable deflection) but also to measure the ankle joint angle; Moltedo et al. [75] used two encoders, one for each purpose; Martinez-Hernandez et al. [81] used a motorized linear potentiometer to measure foot movement, while Kirtas et al. [96] used a potentiometer to measure spring displacement. A total of 42 studies in our review made use of encoders [51], [53], [55], [56], [58], [60], [64], [67], [68], [69], [70], [73], [74], [75], [79], [80], [81], [82], [83], [84], [88], [92], [93], [94], [96], [100], [104], [105], [108], [109], [110], [112], [116], [119], [120], [121], [122], [127], and nine had potentiometers [20], [58], [81], [96], [105], [108], [115], [124], [125].

#### 2) INERTIAL MEASUREMENT UNITS

IMUs (including accelerometers and gyroscopes) are used to measure kinematic information, such as angular position and velocity of links. For example, the authors of [52], [57], and [65] used IMUs for information on the shank, while Cooper et al. [60] and Awad et al. [125] used them on the foot. IMUs are also beneficial for gait event detection, either on their own [70], [74] or in combination with GRF sensors [82], [87]. A total of 28 devices made use of IMUs [52], [54], [55], [57], [60], [65], [70], [72], [74], [79], [80], [81], [82], [85], [87], [91], [97], [105], [112], [113], [114], [117], [119], [121], [122], [123], [125], [127].

### C. MUSCLE MOBILITY SENSORS

#### 1) ELECTROMYOGRAPHY

Among the selected articles, only Jung et al. [94] used EMG data for exoskeleton control. Jung et al. [94] combined the contributions of a powered ankle–foot orthosis with functional electrical stimulation (FES) to generate the desired joint torque. A 1-D convolutional neural network was used to estimate the required FES at different walking speeds based on reference EMG data for tibialis anterior and soleus in healthy individuals. Then, based on the measured EMG, the reference torque is estimated, so the FES controller and the orthosis are actuated accordingly.

#### 2) SHEAR WAVE TENSIOMETRY

Schmitz et al. [86] adopted an innovative method to control the exoskeleton. Knowing that the squared speed of a shear wave travelling across a tendon modulates with the axial force in the tendon [135], shear wave tensiometry noninvasively assesses tendon force using skin-mounted sensors. A tensiometer, therefore, consists of a custom piezoelectric tapper that excites a travelling shear in the tendon, and two miniature accelerometers to measure the motion of the shear wave. The tensiometer was mounted on the Achilles tendon.

### D. MISCELLANEOUS

Bao et al. [76] used a visual sensor—a depth camera—for real-time environment detection; a central pattern generator–multilayer perceptron (CPG-MLP) model is utilized to generate ankle motion trajectories depending on the terrain detected using semantic segmentation.

## VII. CONTROL STRATEGIES

Control methods used in exoskeletons can be classified into different categories depending on the point of view of the reviewers. Exoskeletons normally adopt hierarchical control, namely, high-level, mid-level, and low-level control [34]. In low-level control, the three main control methods are position control, force control, and EMG-based control [2], which track the desired trajectory by adjusting the device state. Three categories are established: high-level, mid-level, and low-level control. On the other hand, high-level control focuses on the user's motion intention, while mid-level control converts the motion intention into a desired trajectory [34]. Examples would be EMG-based control, finite-state control, and proportional–integral–differential control for high, mid, and low levels, respectively. Alternatively, exoskeletons can adopt input-based control methods, which include event-based control (such as finite state) and EMG-based control, or output-based control, such as impedance control [33]. However, many devices combine two or more of the aforementioned strategies by having layered control, as in [51], which uses FSR-based gait phase detection along with position control, or by switching control methods based on the gait phase, as in [73], which uses an event-based state machine detecting heel strike with a footswitch, switches between torque control during the stance phase and position control during the swing phase in independent mode, and applies torque profiles in cooperative mode. For the sake of simplicity, we will consider event-based control and predefined torque profiles for high- and mid-level, along with position and force control for low level.

### A. EVENT-BASED CONTROL

This method uses sensory input, commonly from GRF and/or IMU sensors, to perform gait event (e.g., heel strike) or gait phase detection. For this purpose, FSMs are frequently used to define states and transitions. Martinez-Hernandez et al. [97] used a Bayesian approach together with a competing accumulator to identify gait periods, along with an FSM with three states: "toe-off," "hold," and "heel contact," which correspond to the "assistive" (lift the foot up), "hold," and "release" (move the foot down) operation modes of the exoskeleton, respectively. Choi et al. [64] used a four-state FSM: "weight bearing," "mid-stance," "terminal stance," and "swing," triggered by heel contact, toe contact, heel off, and toe-off, respectively, which are detected from FSR data. Thresholding is sometimes applied to sensor data to identify transitions, as in [50] and [56]. Based on the detected event, actions taken range from

opening/closing a valve [69] to switching between different control techniques, as in [61], which uses position control in swing and force (torque) control in stance. Event-based control was very commonly used [20], [50], [51], [52], [54], [55], [56], [57], [58], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [77], [79], [80], [81], [82], [84], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [101], [102], [103], [104], [105], [106], [108], [110], [111], [112], [113], [114], [115], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126].

### B. PREDEFINED ASSISTANCE PROFILES

Another way to control ankle exoskeletons is by providing timed control profiles, which are normally combined with event detection algorithms (see Section VII-A) [52], [57], [66], [73], [80], [91], [92], [95], [98], [99], [107], [108], [112], [113], [123], [124]. Yeung et al. [52] applied motor torque output profiles during the swing phase, and the level of assistance is adjustable by calibration, along with short bursts of assistance during push-off and weight acceptance. Mooney et al. [92] applied open-loop torque profiles during the stance phase, a slight plantarflexion torque during the controlled dorsiflexion region of the stance phase, and zero torque during swing.

### C. POSITION CONTROL

With position control, an exoskeleton can be controlled so that the user's limb is driven to follow a trajectory based on data from healthy individuals or from the healthy limb in the case of single-limb impairment [2]. The authors of [51], [53], [54], [55], [56], [60], [61], [64], [68], [70], [72], [73], [74], [80], [81], [82], [86], [93], [101], [106], [109], [116], [120], and [122] all applied position control. Velocity control can also be performed [59], [60], [70], [97].

### D. FORCE CONTROL

Force control can take the form of either force, torque, or impedance/admittance feedback loops.

#### 1) FORCE FEEDBACK

In [82], [86], [96], [121], [125], authors implement a force feedback loop. For instance, in [125], a load cell measurement is used to control the exosuit.

#### 2) TORQUE FEEDBACK

In [59], [61], [63], [64], [65], [67], [68], [71], [73], [75], [77], [79], [84], [85], [88], [90], [100], [102], [111], [119], [126], authors use torque feedback. For instance, in [65], a currentbased torque signal was used to control the exosuit, while in [67] the overall exoskeleton and ankle joint torque were used to match a reference torque signal.

#### 3) IMPEDANCE/ADMITTANCE FEEDBACK

In [59], [61], [63], [64], [65], [67], [68], [71], [73], [75], [77], [79], [84], [85], [88], [90], [100], [102], [111], [119], [126], authors rely on torque feedback. For instance, in [65], a current based torque signal was used to control the exosuit, while in [67] the overall exoskeleton and ankle joint torque were used to match a reference torque signal.

### E. ELECTRONIC SYSTEMS

Upon looking at control strategies, it is important to consider the electronic system deployed in the exoskeleton, in particular, the controller board, where the control algorithm runs, and the battery used to power the device. The most commonly used microcontrollers are Arduino [50], [51], [52], [54], [59], [65], [81], [104], [106], [107], [111], [114], [117], [123] and STM32 [55], [72], [74], [78], [121] variants, along with 32-bit ARM microprocessor Teensy 3.6 [63], [66], [77], [84], [95], National Instruments myRIO/CompactRIO, which combine an ARM microprocessor and a Xilinx field-programmable gate array (FPGA) [69], [79], [96], [97], [113], and digital positioning controllers [55], [116]. Motor drivers are required to interface to the motors [51], [53], [56], [59], [63], [66], [68], [69], [70], [73], [74], [77], [84], [88], [96], [97], [106], [108], [109], [111], [113], [119], [121]. As all the reviewed devices are portable, batteries are necessary to power the system, with capacities ranging from 910 mAh [71] to a massive 44 800 mAh, equivalent to 8 h of device use [120]. Lithium polymer batteries are quite common [50], [51], [53], [65], [67], [77], [80], [83], [88], [92], [95], [96], [98], [105], [109], [116]. While Allen et al. [95] used an 11.1-V battery to power the electronics, the actuators they used were dielectric muscle actuators (DEAs), a type of artificial muscles, which required a capacitor bank consisting of two high-voltage capacitors, an inductor bank, and a high-voltage dc–dc converter to convert the 11.1-V input to a high voltage (up to 6 kV) for powering the DEA strap. On the other hand, some pneumatic-actuated exoskeletons use valve control, which eliminates the need for an external power source and controller [89], [118].

## VIII. DESIGN EVALUATION: DEVICE MASS AND COMPLEXITY VERSUS METABOLIC BENEFITS

Looking at the prototypes reported in the literature, we can find a large variation in their weights, ranging from 0.78 kg for a unilateral orthosis to 10 kg for a bilateral exosuit. Out of the 54 devices with known weight, 32 exoskeletons were rigid, along with 14 soft and eight hybrid devices; 19 exoskeletons overall were bilateral, while 35 were unilateral (see Fig. 4).

Supplementary Fig. A shows a graphical view of the 54 devices with reported mass and distinguishes between 1) rigid and soft/hybrid and 2) unilateral and bilateral, while using transparent markers for those providing metabolic consumption benefits, such that the size of the marker represents the amount of metabolic savings.

It can be seen from the graph that soft/hybrid devices made their first appearance in 2014 but only became popular from 2017 onwards, even outnumbering their rigid counterparts in 2023.

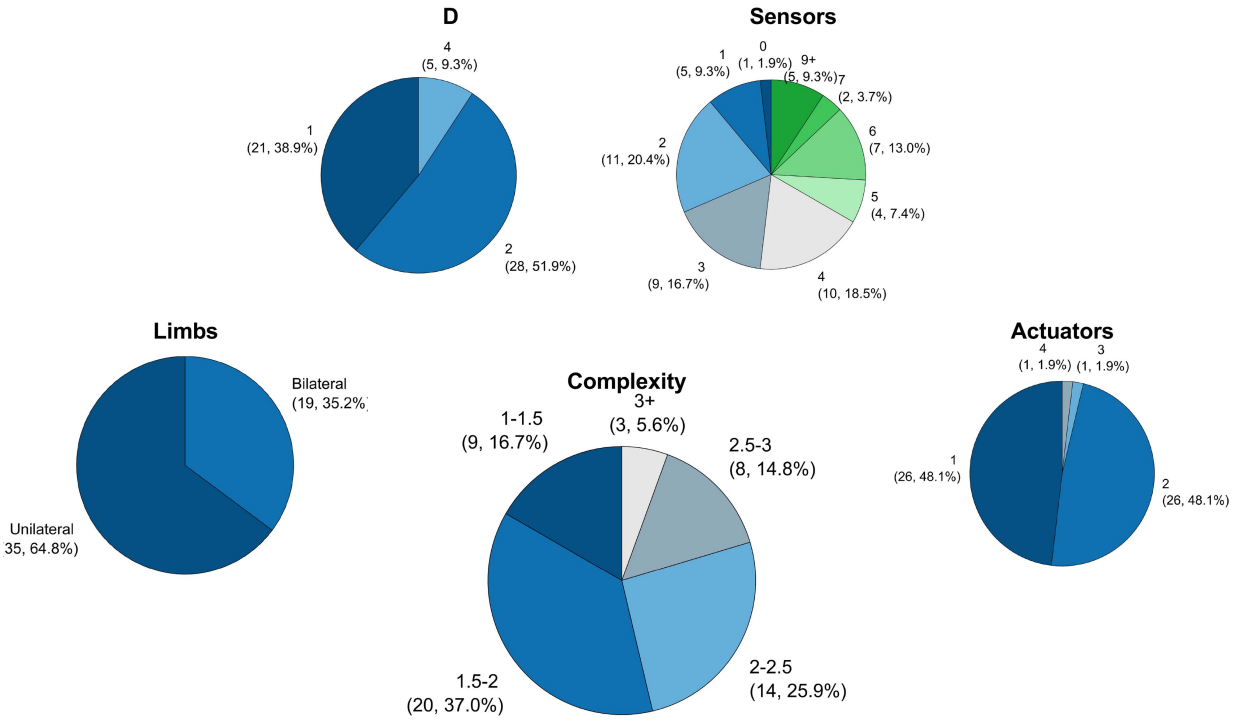



**FIGURE 4.** Distribution of the 79 reviewed articles by number of assisted limbs, *D* factor, sensors, actuators, and complexity.

### A. COMPLEXITY INDEX

Apart from weight, another factor to be optimized during exoskeleton design is complexity. Hence, we define the exoskeleton complexity index, calculated using a weighted sum, where each factor's contribution to the index reflects its relative impact on design complexity

$$\text{Complexity Index} = 0.3\,L + 0.3\,D + 0.15\,S + 0.25\,A. \quad (1)$$

Here, $L$ represents the number of assisted limbs, i.e., 1 for unilateral and 2 for bilateral; bilateral assistance increases the design's mechanical, control, and power demands, which is roughly as significant as DOFs or the number of actuators in terms of complexity. Hence, a high coefficient should be used. $D$ can be thought of as twice the number of DOFs (range 1–4); as each additional DOF often requires additional complexity in terms of mechanics, control, and ergonomics. It is, therefore, a major factor and should have a high coefficient. $S$ represents the number of sensors [136] (range 1–20, but many have up to 5 only); sensors are essential for feedback and adaptive control, and more sensors generally mean greater complexity in integration and data processing. However, their complexity impact is typically lower than actuators; and they are normally lightweight. A lower weight coefficient can be used. $A$ represents the number of actuators [136] (range 1–4); actuators significantly impact complexity because each requires precise control and power, and adds weight, hence the high coefficient.

The coefficient values were chosen in a way to balance between the factors based on the range of each factor and the range where most devices lie. For example, the lowest coefficient is used for the number of sensors in order not to exaggerate the impact of very high numbers of sensors, knowing that the number of sensors has the widest range. $D$ can go up to four, but devices typically have two (dorsiflexion/plantarflexion). Actuators can go up to four in one instance, but usually one or two are enough. Also, many bilateral devices have two actuators and more sensors, which was already reflected by the $L$ factor, and influenced the choice of slightly lower weights for $A$ and $S$.

### B. COMPLEXITY VERSUS TIME

Fig. 5 suggests an increasing complexity over time: the number of sensors is increasing as technological advancements in sensors, electronics, and miniaturization are allowing for more integrability, whereas the number of actuators is decreasing as more compact and powerful actuators become available.

### C. METABOLIC SAVINGS VERSUS COMPLEXITY AND WEIGHT

While it seems that metabolic savings tend to increase with complexity and decrease with higher device weight, we can probably say that the best compromise between metabolic savings, complexity, and weight can be achieved with approximately a complexity of up to 2.5 and a weight of up to 4 kg based on Figs. 6 and 7.

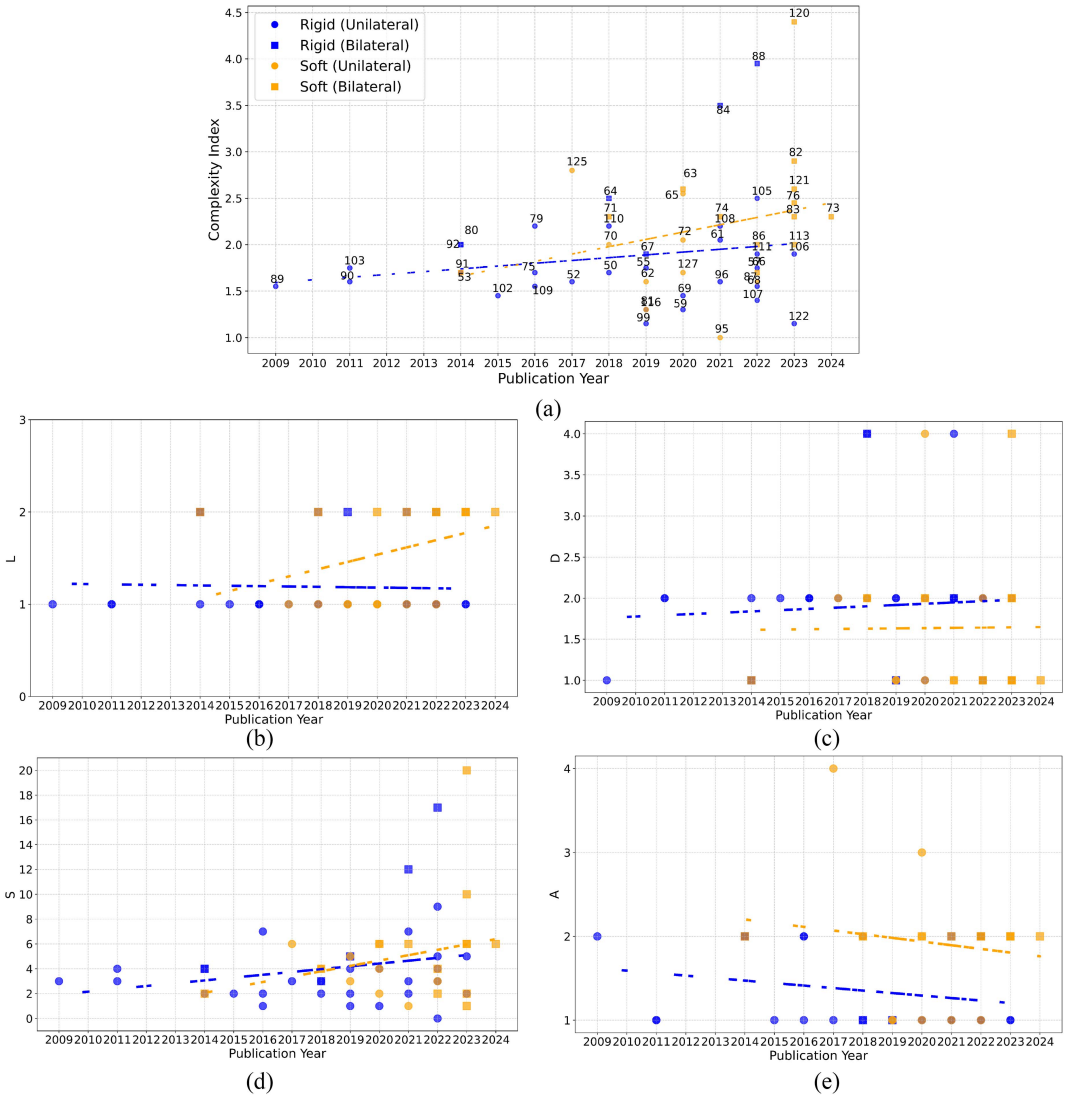



**FIGURE 5.** (a) Exoskeleton complexity index and the factors (b) *L*, (c) *D*, (d) *S*, and (e) *A* over time. Linear trendlines are shown in dashed lines and follow the same color coding (blue for rigid and orange for soft).

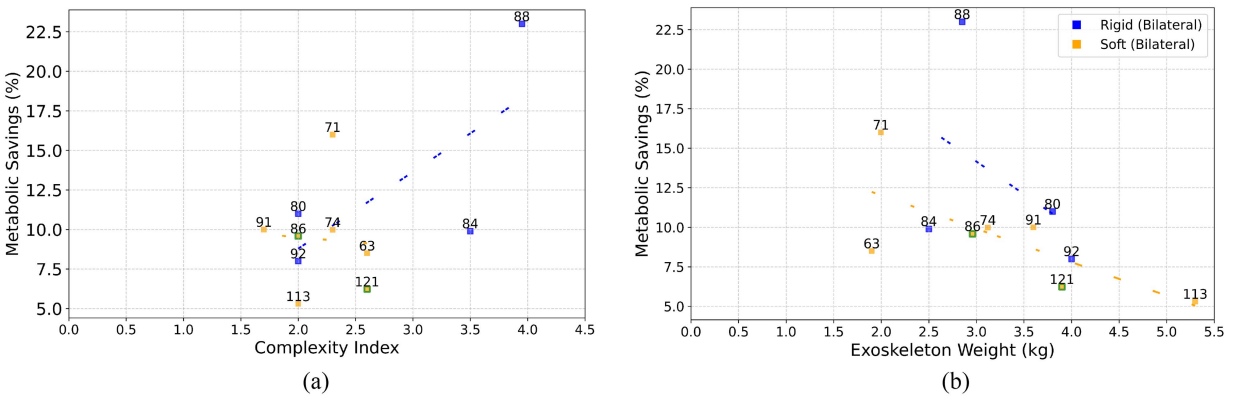



**FIGURE 6.** (a) Metabolic savings versus complexity. (b) Metabolic savings versus device weight.

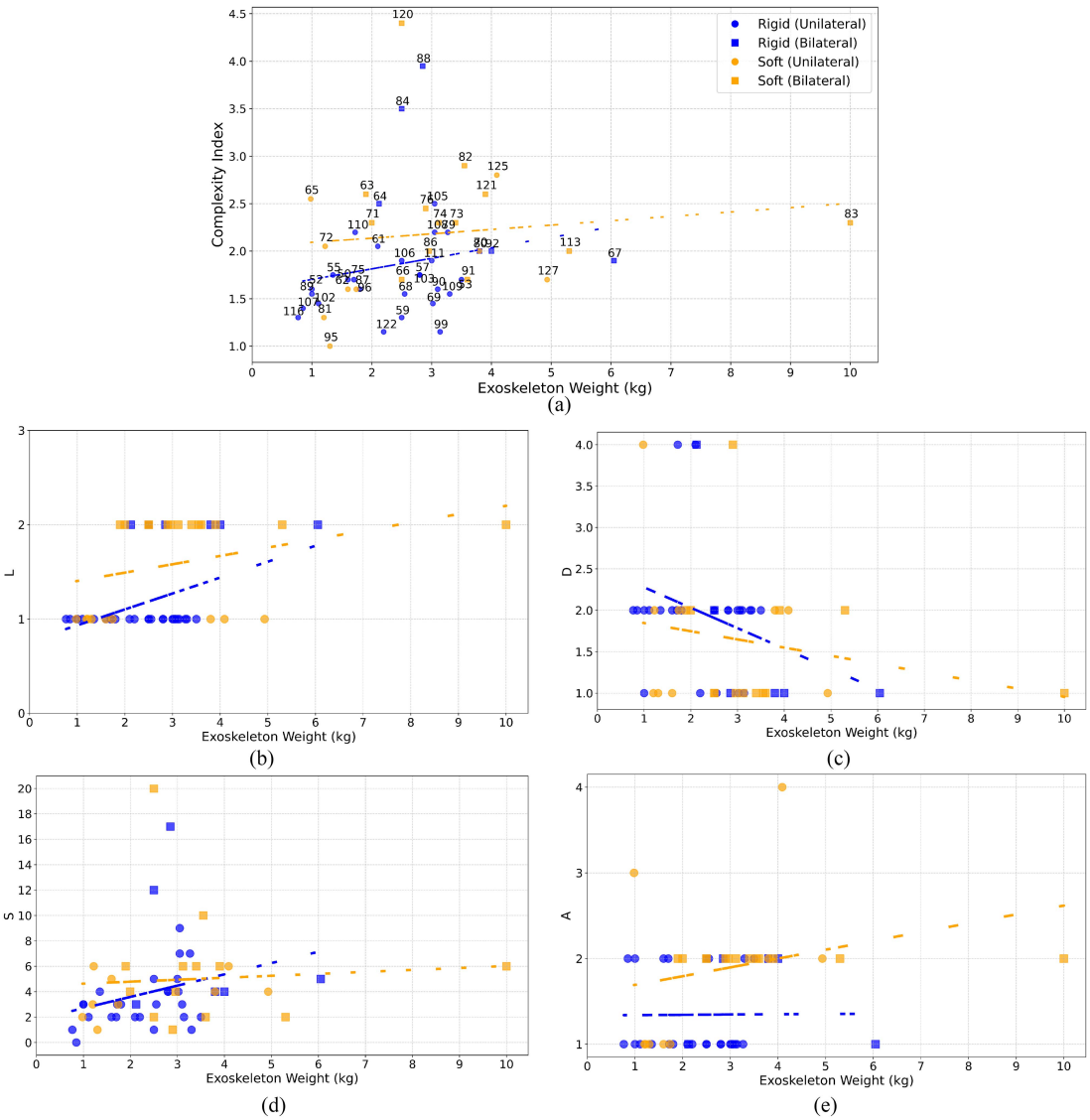



**FIGURE 7.** (a)–(e) Exoskeleton complexity versus weight.

### *D. COMPLEXITY VERSUS WEIGHT*

Fig. 7 suggests an increasing complexity with increasing weight, because a higher complexity usually involves adding components, as providing bilateral assistance and increasing the number of actuators and/or sensors are also correlated with increasing weight. However, it is interesting to see that extra DOFs do not add weight, whereas the numbers of actuators and assisted limbs do; in the case of the heaviest device [83] (10 kg), which only assists plantarflexion ($D = 1$) and has moderate numbers of actuators (two) and sensors (six), it seems that the backpack where the actuators and controllers are placed is responsible for the extra mass.

## IX. USER GROUPS

Although elderly and stroke survivors are the demographic of interest in this review, exoskeletons, in general, and ankle exoskeletons, in particular, have different applications.

Exoskeletons can be classified in two categories depending on their purpose/application: medical or nonmedical. Medical exoskeletons focus on restoring limited/lost body functions due to medical conditions, such as spinal cord injury, neurological disorders, trauma (e.g., stroke), cerebral palsy, etc. These exoskeletons are regulated as medical devices and are usually used for patient training in hospitals and rehabilitation centers under the supervision of health care professionals. Nonmedical exoskeletons usually come as augmentation devices, as they assist healthy people in carrying out some activities while providing them with physical support. These devices could provide strength supplementation or augmentation for different application scenarios. For example, in the context of healthy aging, elderly people can be supported to perform activities of daily living. Another application is providing assistance to healthy individuals to perform physically demanding tasks, such as carrying heavy weights and walking on rough terrains

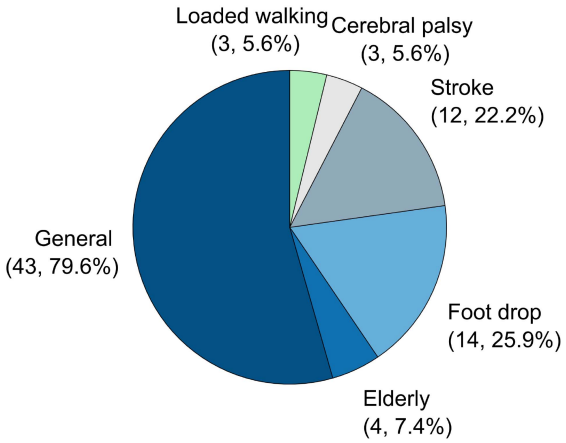



**FIGURE 8.** **Distribution of the 79 reviewed articles by target user category.**

(e.g., soldiers), speed augmentation, or reduction of the effort and metabolic consumption required for a specific activity.

Fig. 8 shows the distribution of the 79 reviewed articles by the target user category. The majority of articles, however, did not target a specific audience. A total of 26 (32.9%) exoskeletons are stroke-related (stroke and foot drop), along with the three devices targeting cerebral palsy, and hence, they belong to the medical category. Only four exoskeletons target elderly specifically, and three devices are applied to loaded walking, thereby falling into the nonmedical category.

## X. COMMERCIAL ANKLE EXOSKELETONS

Many multiple-joint exoskeletons have been commercialized, with examples including Ekso [137], ReWalk [138], Indego [139], Rex [140], and HAL [141]. In a web search on commercially available ankle exoskeletons [142], five systems were identified. Ankle H3 [143] (foot clearance) is aimed at research use; AMBLE [144] and ReStore [145] are meant for the supervised clinical rehabilitation of stroke/foot drop patients. Dephy ExoBoot was initially developed for military purposes but now targets the augmentation of a general audience [146] and is also used in research [147], similarly to the Biomotum SPARK [148], which can be used in research, rehabilitation, or every day.

All five exoskeletons are motor actuated. Dephy ExoBoot is based on [91] and [92], and the ReStore is based on [125]. GRF/ground contact sensors are commonly used in the AMBLE, Ankle H3, and ReStore. The Ankle H3 and SPARK have joint position and torque sensors.

## XI. TRENDS AND APPLICATIONS

Recent developments in ankle exoskeletons reflect a shift from rigid and bulky designs toward soft, flexible, lightweight, and intelligent devices. This transition involves replacing traditional rigid actuation systems and mechanical structures with compliant actuators and soft materials to enhance comfort and usability. In addition, innovative energy-harvesting mechanisms improve assistance efficiency. Different types of sensors are made available, but they have to be carefully considered regarding their features and limitations in exoskeleton control; Wang et al. [149] provided an overview of wearable sensors and commercial wearable products for motion control. For instance, fiber optic sensors (e.g., fiber Bragg gratings) are promising for applications in the fields of biomechanics and rehabilitation, as they can be used in insoles for GRF sensing as well as for monitoring joint angles [150], [151]. Advances in control strategies include adaptive and personalized controllers based on intention recognition, enhanced by artificial intelligence (AI) methods that utilize data from sensors, such as EMG, IMUs, and pressure sensors. These advancements enable more accurate prediction of user intentions, resulting in personalized, effective, and natural assistance.

Ankle exoskeletons have applications primarily in rehabilitation and augmentation. Although significant progress has been made, most ankle exoskeletons have only been validated within laboratory or controlled clinical settings, and substantial gaps remain before they can be widely adopted in wider real-world environments. Driven by advancements in AI technologies, potential directions include developing highly personalized devices capable of real-time adaptation to individual needs for medical and nonmedical scenarios. Integrating wearable sensors can facilitate continuous health monitoring and remote health care. Inspired by Furuya et al. [152], an exoskeleton designed for athletes is capable of improving their performance by enhancing specialized motor skills. In addition, ankle exoskeletons have the potential to be developed into haptic devices capable of simulating realistic feedback at the ankle joint to enhance physical human–robot interaction studies [153], [154], [155].

## XII. CONCLUSION

This article reviewed the latest advancements in wearable sensors and control strategies for active ankle exoskeletons and established a classification of the devices based on a defined complexity index that accounts for the sensor modalities, along with relevant parameters associated with mechanical rigidity, actuation, and control strategies, while identifying the target users, device weight, and associated metabolic savings. The complexity index allowed us to perform a comparative assessment of the design complexity of ankle exoskeletons against device functionality, resulting from the achieved metabolic savings and weight.

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